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(54) **KEY SPLITTING**

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H04L 12/417	(2006.01)
H04L 12/46	(2006.01)
H04L 9/00	(2022.01)
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CPC ***H04L 9/085*** (2013.01); ***H04L 9/008*** (2013.01); ***H04L 9/0861*** (2013.01); ***H04L 9/0877*** (2013.01); ***H04L 9/0894*** (2013.01); ***H04L 9/14*** (2013.01); ***H04L 12/417*** (2013.01); ***H04L 12/4625*** (2013.01); *H04L 2209/04* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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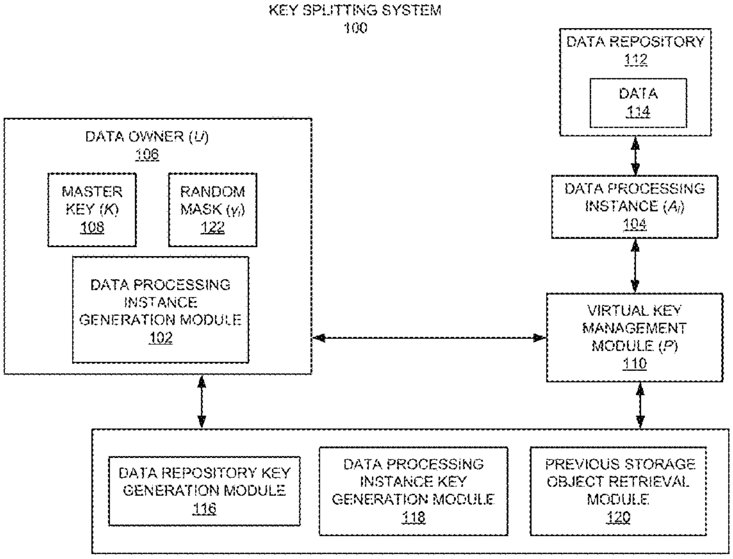
(57) **ABSTRACT**

According to an example, key splitting may include utilizing a masked version of a master key that is masked by using a mask.

18 Claims, 8 Drawing Sheets


KEY SPLITTING SYSTEM
100
DATA REPOSITORY
112
DATA
114
DATA OWNER (U)
106
MASTER KEY (K)
108
RANDOM MASK (y_i)
122
DATA PROCESSING INSTANCE GENERATION MODULE
102
DATA PROCESSING INSTANCE (A_i)
104
VIRTUAL KEY MANAGEMENT MODULE (P)
110
DATA REPOSITORY KEY GENERATION MODULE
116
DATA PROCESSING INSTANCE KEY GENERATION MODULE
118
PREVIOUS STORAGE OBJECT RETRIEVAL MODULE
120

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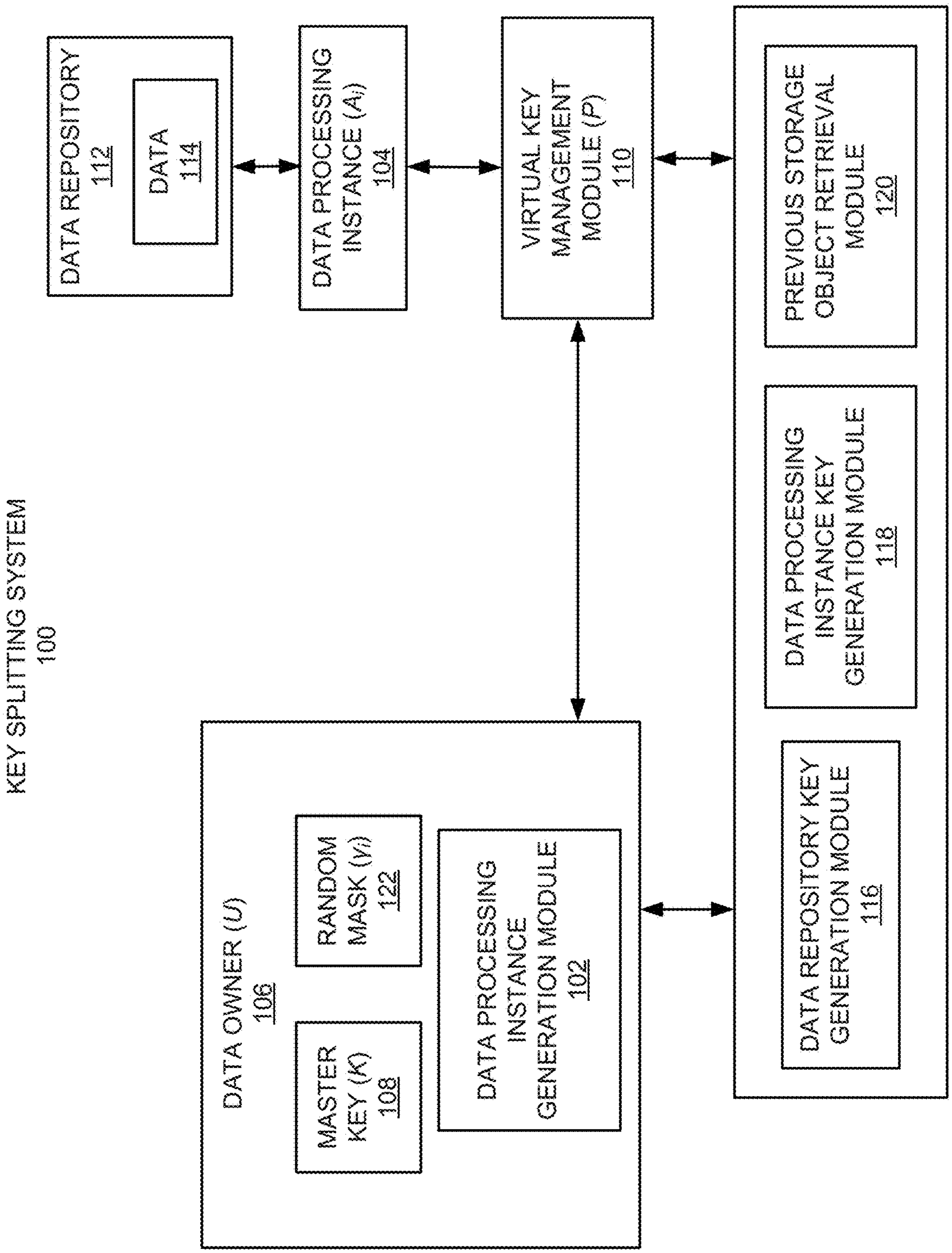
KEY SPLITTING SYSTEM
100
DATA REPOSITORY
112
DATA
114
DATA PROCESSING INSTANCE (A_i)
104
VIRTUAL KEY MANAGEMENT MODULE (P)
110
PREVIOUS STORAGE OBJECT RETRIEVAL MODULE
120
DATA PROCESSING INSTANCE KEY GENERATION MODULE
118
DATA REPOSITORY KEY GENERATION MODULE
116
DATA OWNER (U)
106
MASTER KEY (K)
108
RANDOM MASK (y_i)
122
DATA PROCESSING INSTANCE GENERATION MODULE
102

FIG. 1

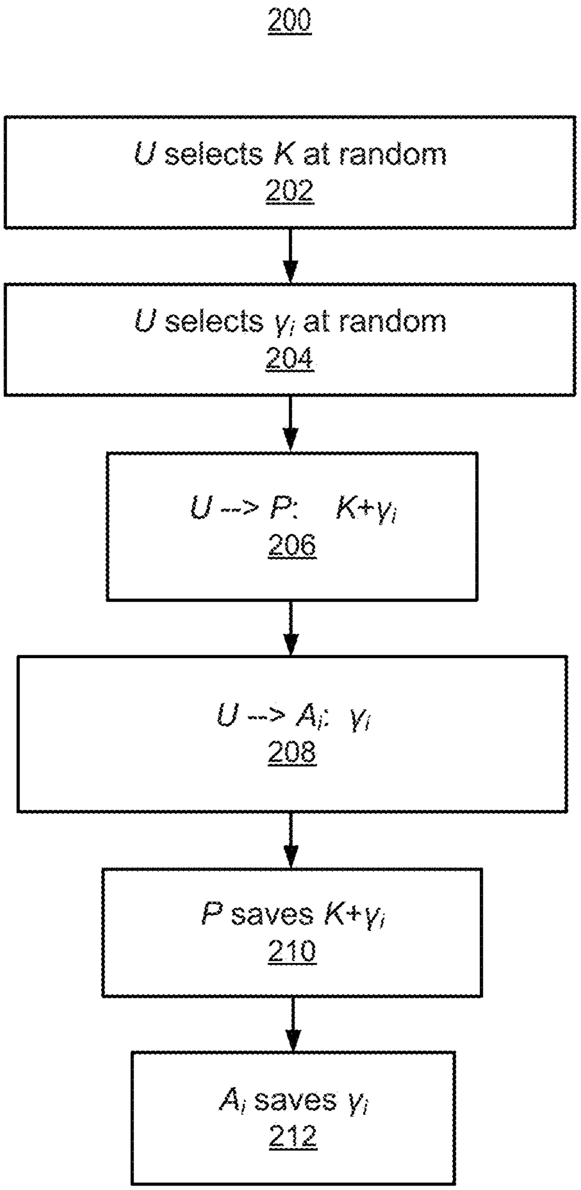
200
U selects K at random
202
U selects y_i at random
204
U --> P: $K+y_i$
206
U --> A_i: y_i
208
P saves $K+y_i$
210
A_i saves y_i
212

FIG. 2

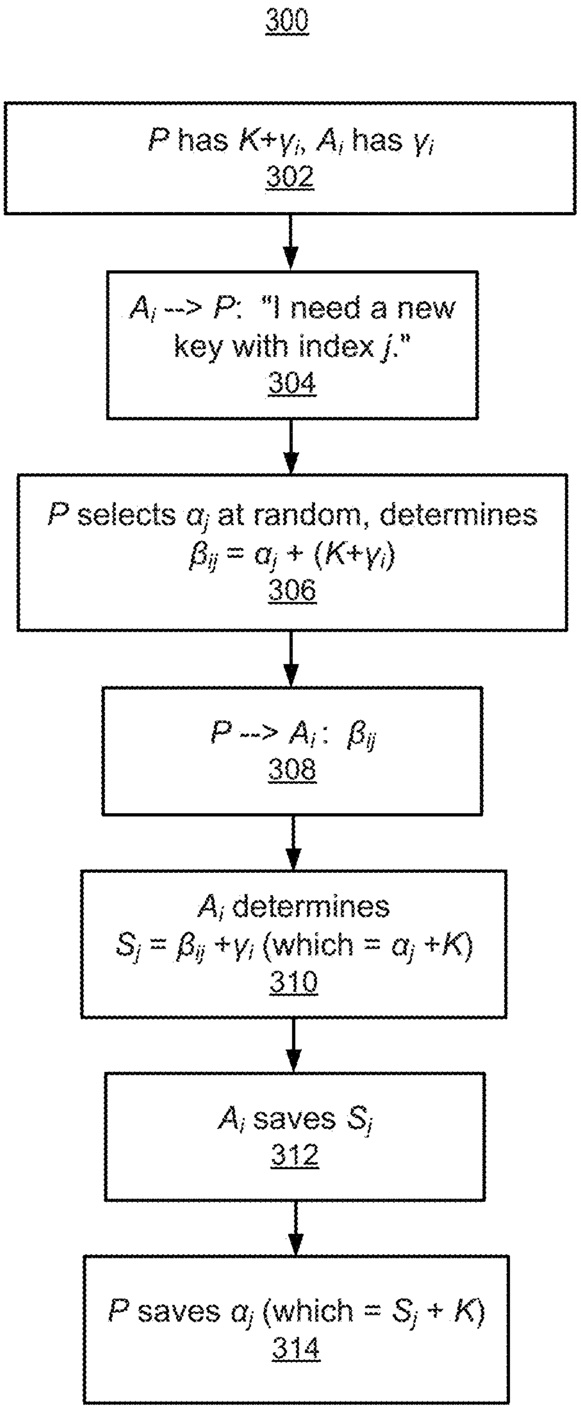
300
P has $K+\gamma_i$, A_i has γ_i
302
A_i --> P: "I need a new key with index j."
304
P selects α_j at random, determines $\beta_{ij} = \alpha_j + (K+\gamma_i)$
306
P --> A_i: β_{ij}
308
A_i determines $S_j = \beta_{ij} + \gamma_i$ (which = $\alpha_j + K$)
310
A_i saves S_j
312
P saves α_j (which = $S_j + K$)
314

FIG. 3

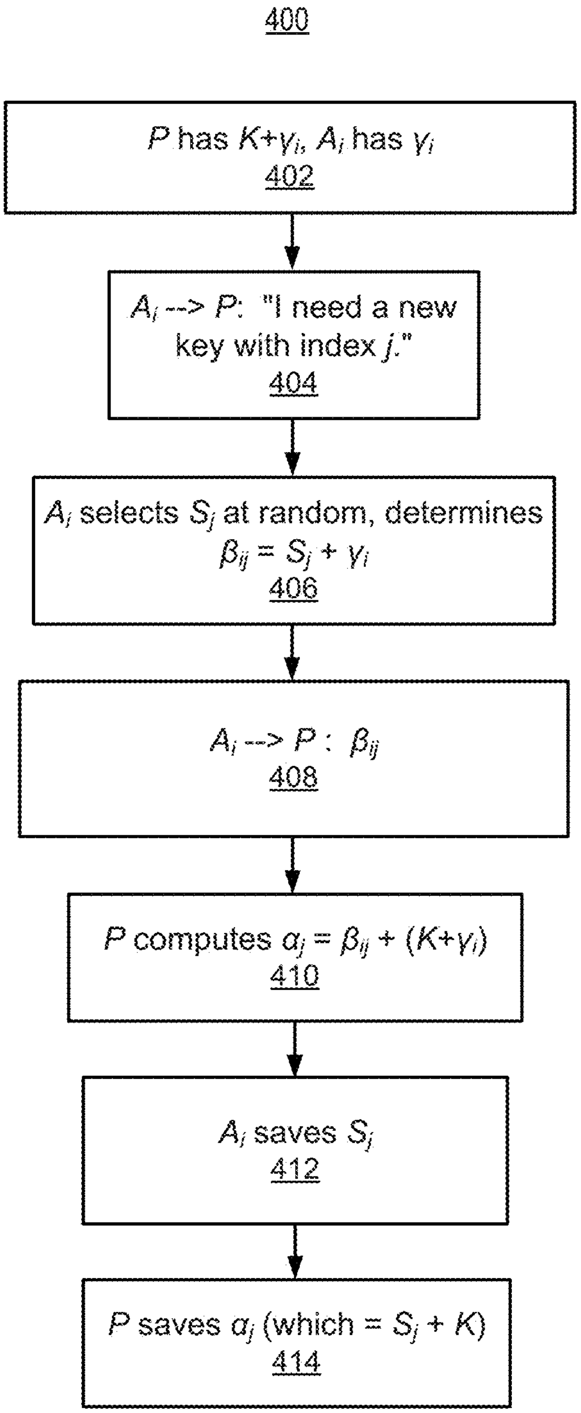
400
P has $K+\gamma_i$, A_i has γ_i
402
A_i --> P: "I need a new key with index j."
404
A_i selects S_j at random, determines $\beta_{ij} = S_j + \gamma_i$
406
A_i --> P : β_{ij}
408
P computes $\alpha_j = \beta_{ij} + (K+\gamma_i)$
410
A_i saves S_j
412
P saves α_j (which = $S_j + K$)
414

FIG. 4

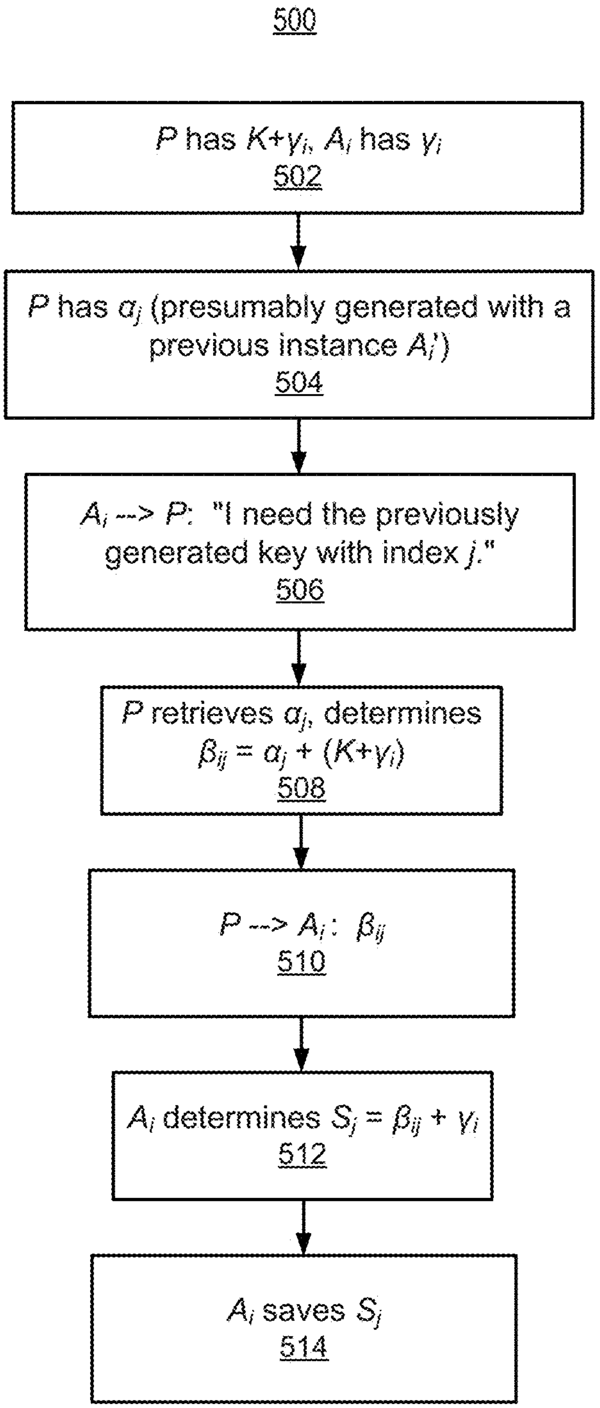
500
P has $K+\gamma_i$, A_i has γ_i
502
P has α_j (presumably generated with a previous instance A_i')
504
A_i --> P: "I need the previously generated key with index j."
506
P retrieves α_j, determines $\beta_{ij} = \alpha_j + (K+\gamma_i)$
508
P --> A_i: β_{ij}
510
A_i determines $S_j = \beta_{ij} + \gamma_i$
512
A_i saves S_j
514

FIG. 5

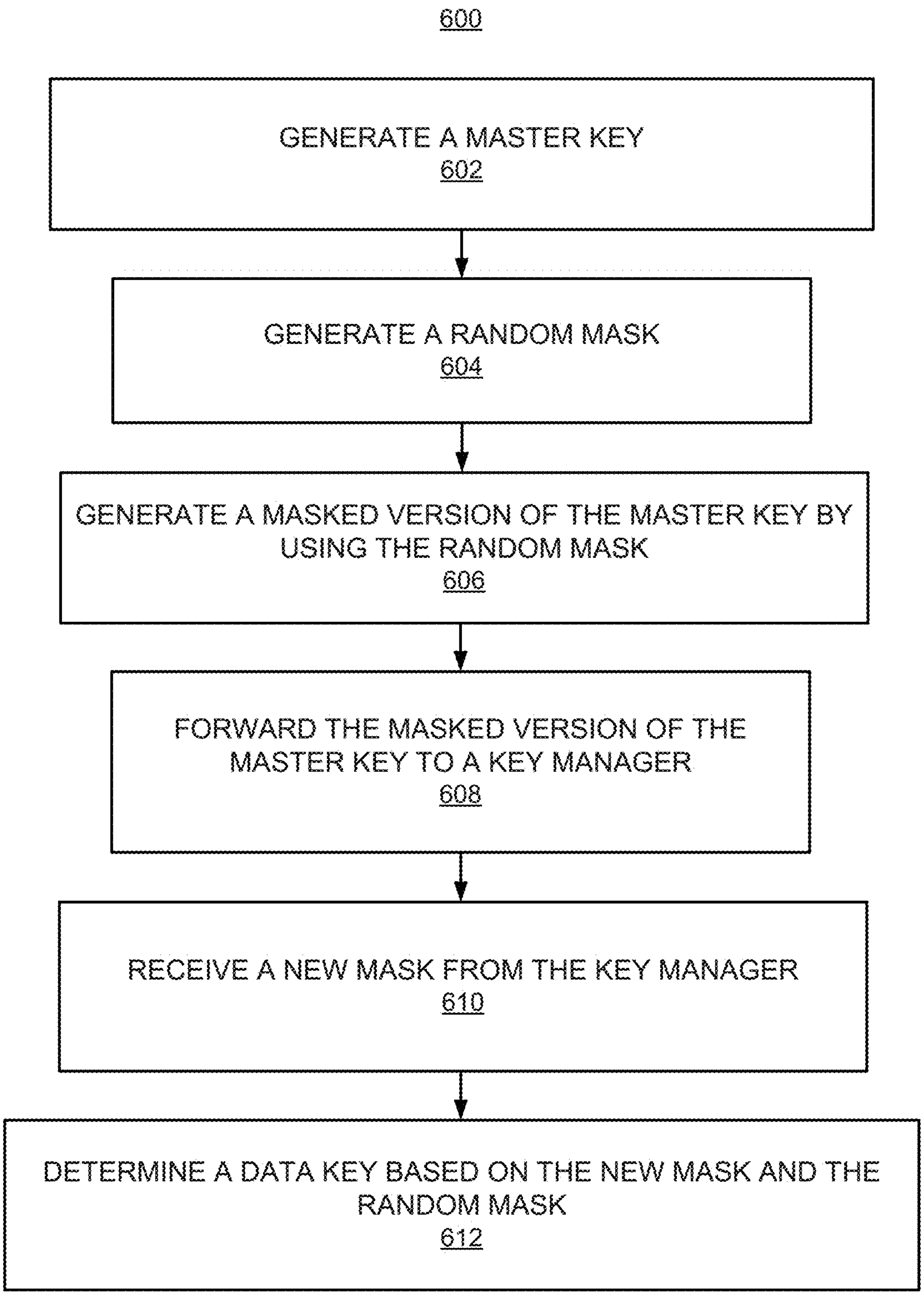
600
GENERATE A MASTER KEY
602
GENERATE A RANDOM MASK
604
GENERATE A MASKED VERSION OF THE MASTER KEY BY USING THE RANDOM MASK
606
FORWARD THE MASKED VERSION OF THE MASTER KEY TO A KEY MANAGER
608
RECEIVE A NEW MASK FROM THE KEY MANAGER
610
DETERMINE A DATA KEY BASED ON THE NEW MASK AND THE RANDOM MASK
612

FIG. 6

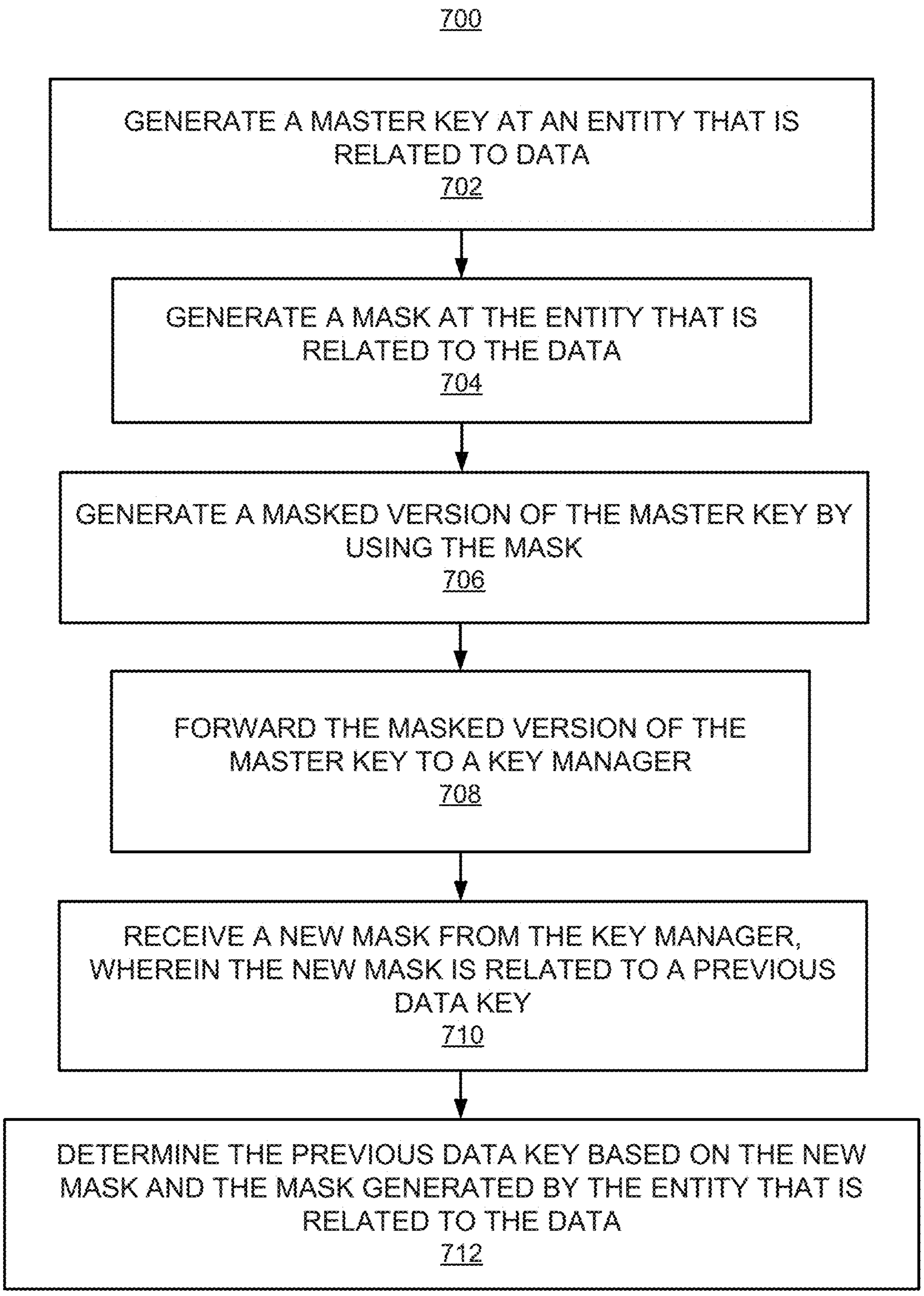
700
GENERATE A MASTER KEY AT AN ENTITY THAT IS RELATED TO DATA
702
GENERATE A MASK AT THE ENTITY THAT IS RELATED TO THE DATA
704
GENERATE A MASKED VERSION OF THE MASTER KEY BY USING THE MASK
706
FORWARD THE MASKED VERSION OF THE MASTER KEY TO A KEY MANAGER
708
RECEIVE A NEW MASK FROM THE KEY MANAGER, WHEREIN THE NEW MASK IS RELATED TO A PREVIOUS DATA KEY
710
DETERMINE THE PREVIOUS DATA KEY BASED ON THE NEW MASK AND THE MASK GENERATED BY THE ENTITY THAT IS RELATED TO THE DATA
712

FIG. 7

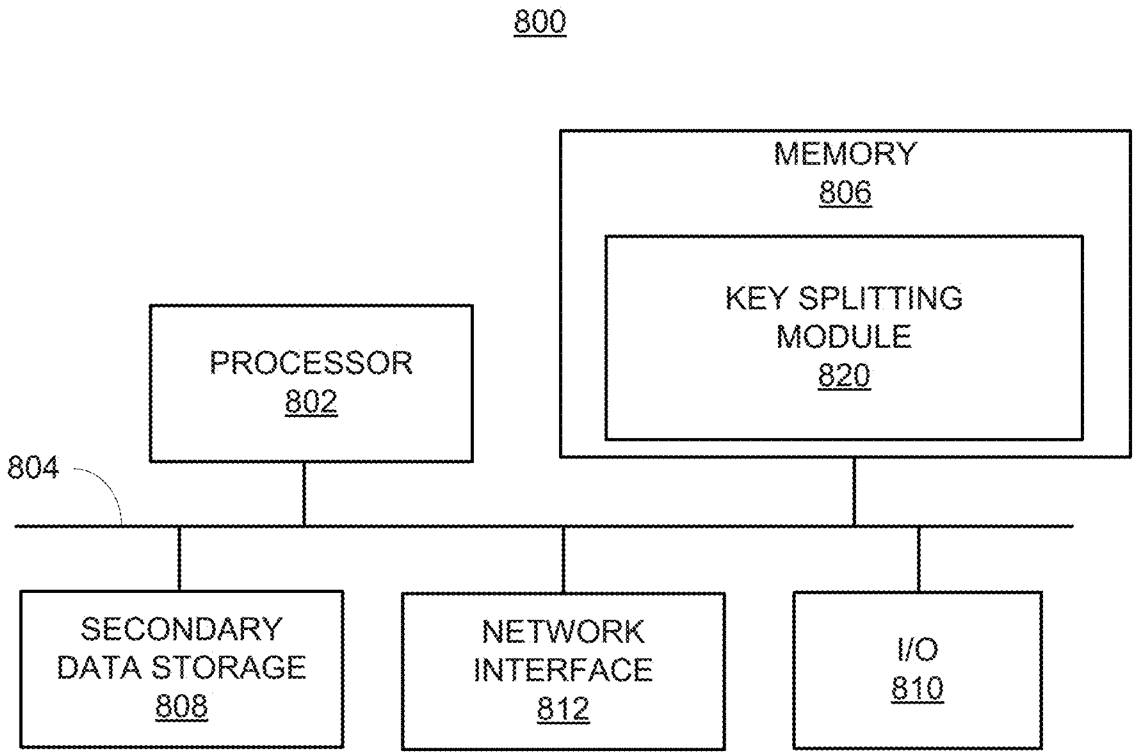
800
MEMORY
806
KEY SPLITTING
MODULE
820
PROCESSOR
802
804
SECONDARY
DATA STORAGE
808
NETWORK
INTERFACE
812
I/O
810

FIG. 8

KEY SPLITTING

BACKGROUND

Encryption is the process of encoding information such that the encrypted information is read by authorized entities. With respect to encryption, the information, which is typically referred to as plaintext, is encrypted using an encryption process. The encrypted information is referred to as ciphertext. In order to read the ciphertext, a key is typically used to decrypt the ciphertext.

BRIEF DESCRIPTION OF DRAWINGS

Features of the present disclosure are illustrated by way of example and not limited in the following figure(s), in which like numerals indicate like elements, in which:

FIG. **1** illustrates an architecture of a key splitting system, according to an example of the present disclosure;

FIG. **2** illustrates a flowchart of a data processing instance generation protocol for the key splitting system of FIG. **1**, according to an example of the present disclosure;

FIG. **3** illustrates a flowchart of a data repository key generation protocol for the key splitting system of FIG. **1**, according to an example of the present disclosure;

FIG. **4** illustrates a flowchart of a data processing instance key generation protocol for the key splitting system of FIG. **1**, according to an example of the present disclosure;

FIG. **5** illustrates a flowchart of a previous storage object retrieval protocol for the key splitting system of FIG. **1**, according to an example of the present disclosure;

FIG. **6** illustrates a method for key splitting, according to an example of the present disclosure;

FIG. **7** illustrates further details of the method for key splitting, according to an example of the present disclosure; and

FIG. **8** illustrates a computer system, according to an example of the present disclosure.

DETAILED DESCRIPTION

For simplicity and illustrative purposes, the present disclosure is described by referring mainly to examples. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present disclosure. It will be readily apparent however, that the present disclosure may be practiced without limitation to these specific details. In other instances, some methods and structures have not been described in detail so as not to unnecessarily obscure the present disclosure.

Throughout the present disclosure, the terms “a” and “an” are intended to denote at least one of a particular element. As used herein, the term “includes” means includes but not limited to, the term “including” means including but not limited to. The term “based on” means based at least in part on.

Symmetric keys for encryption and decryption of data typically include the use of the same cryptographic keys for both encryption of plaintext and decryption of ciphertext. With respect to symmetric keys, the keys are typically identical, or there may be a transformation that is performed between the two keys. Asymmetric keys for encryption and decryption of data typically include two separate keys, one of which is secret (or private) and one of which is public. With regard to encryption and decryption of data, key splitting typically includes the division of a key or decryption process into two or more parts so that no part in itself may be used without reconstructing the key by uniting all of its parts.

Authentication processes may include processes to determine whether the data that is received is the data that was sent. Authentication processes may also include processes related to validation of the authenticity of data by using, for example, hash-based message authentication (HMAC)), and other validation techniques.

Key management may include the management of keys for encryption, decryption, and authentication of data, and/or for the generation of additional keys. For example, for key management, each master key and its corresponding set of encrypted data items may be placed under the control of a single data owner. This type of key management may be used as part of computing systems that provide cryptographic services that use symmetric-key cryptographic mechanisms (which include symmetric encryption and symmetric authentication processes). For such symmetric key based cryptographic services, the sender and the receiver of a message, or the writer and the reader of a stored file, generally share the same specific encryption/decryption key or the same specific authentication key, or one of each. Access to this key may be managed by a key manager that may include key splitting capabilities.

As described herein, key splitting typically includes the division of a key or the division of a decryption process into two or more parts so that no part in itself may be used to reconstruct the key. Rather, each part may need to be united to reconstruct the key. Thus, key splitting provides a data owner (hereinafter designated U, or user U) control of aspects such as encryption, decryption, and authentication of data by preventing other entities from ascertaining the key or the decryption process.

With respect to key splitting, the data owner U may utilize a key manager (hereinafter designated P) to manage keys that are used for data protection. The data owner U may create ephemeral data processing instances (with a specific i^{th} data processing instance being designated as A_i) that provide for data protection. For example, an ephemeral data processing instance may perform data encryption or decryption on behalf of the data owner U on a set of data, and thereafter, the ephemeral data processing instance may be discarded. The key manager may not be trusted with having knowledge of the values of the keys.

In some examples, communication with the key manager P may use a partially homomorphic encryption technique, such as ElGamal encryption. The ElGamal encryption technique is an asymmetric key encryption process for public-key cryptography which is based on the Diffie-Hellman key exchange. With respect to communication with the key manager P, other types of encryption techniques may be used as well.

With respect to key splitting, the data owner U may create a master key (hereinafter designated K). Specific keys that are used to manage data objects (i.e., parts of the data owned by the data owner U) on behalf of the data owner may be derived from the master key K. In order to handle specific keys for individual data objects, the data owner U may initiate the creation of an ephemeral data processing instance A_i, and may send to the data processing instance A_i an encryption of the master key K under the key manager's public key. The data processing instance A_i may generate a random mask γ_i.

The data processing instance A_i may use the homomorphic property of an asymmetric key encryption process to combine an encryption of the random mask γ_i with the encryption of the master key K. The homomorphic property may refer to a form of encryption which allows specific types of computations to be carried out on ciphertext and to generate an encrypted result which, when decrypted, matches the result of operations performed on the original text that is used to generate the ciphertext. In this example, the resulting ciphertext generated by the combination of the encryption of the random mask γ_i and the master key K is an encryption of $K*\gamma_i$ (i.e., the product of K and H. The ciphertext of K and γ_i may be determined in the group structure (e.g., a group G for ElGamal encryption), underlying the asymmetric key encryption process that includes the homomorphic property. The data processing instance A_i may send this ciphertext to the key manager P. Further, the data processing instance A_i may record the value of the random mask γ_i.

The random mask γ_i may be used as a mask shared by the key manager P and the ephemeral instantiation of the data processing instance. The random mask γ_i may be shared implicitly, in that the key manager P does not know the value of the random mask γ_i. The key manager P thus invokes the use of the random mask γ_i through its implicit but not explicit knowledge. The key manager P may use a secret key to decrypt the masked master key (i.e., the ciphertext of K and γ_i) to obtain the value $K*\gamma_i$ (the product of K and γ_i), and store the value for communication with this data processing instance A_i.

A specific key for encryption, decryption, and/or other authentication of an individual data object may be created to be of the form α_j/K, where α_j is a random value, so that the data processing instance A_i knows the key, while the key manager P knows α_j and stores α_j as a mask for this key. For example, the key manager may select a random value α_j, and send $\alpha_i/(K*\gamma_i)$ to the data processing instance A_i that knows γ_i, so that the data processing instance may determine $[\alpha_j/(K*\gamma_i)]\gamma_i$ to recover α_j/K. These values related to α_j, K, and γ_i, and all related operations may be in the underlying group (e.g., a group G for ElGamal encryption) that includes the homomorphic property. The processes described above with respect to creation of a specific key for an individual data object may be used later, after this data processing instance A_i is no longer in existence, to allow the key manager P to provide for a newly created data processing instance to recover the same key, using the original mask α_j for this key α_j/K, and the new value of $\gamma_{i'}$ that is used as its mask shared with this data processing instance.

According to examples, a key splitting system and a method for key splitting are disclosed herein. With respect to key splitting, the system and method may generally utilize any secure communications system, without the need for a homomorphic encryption technique. Non-limiting examples of secure communications systems may include systems that use secure asymmetric encryption techniques such as RSA, elliptic curve cryptography, etc. Homomorphic encryption may be generally described as a form of encryption which allows specific types of computations to be carried out on ciphertext and generate an encrypted result which, when decrypted, matches the result of operations performed on the plaintext. The avoidance of the need to use the homomorphic encryption techniques may reduce computational cost (e.g., processing time, storage, energy usage, etc.). For example, with respect to use of the asymmetric key encryption processes that include a homomorphic property, such techniques may be computationally cost intensive based on the use of relatively longer group elements (e.g., 2048 bits long), compared to relatively shorter bit-strings (e.g., 128 or 256 bits long) that are usable with the example system and method disclosed herein.

For the example system and method disclosed herein, the random mask γ_i may be selected by the data owner (i.e., the data owner U may select a random value for the mask γ_i), such that an asymmetric encryption technique may be used for key splitting. With respect to the term data owner U as used herein, the functionality described as performed by the data owner U and the information related to the data owner U may be performed by and related to a data owner computing device. Generally, for the system and method disclosed herein, the data owner U may select a random mask γ_i, encrypt γ_i*K under the key manager's public key, and send the ciphertext along with the random mask γ_i to the data processing instance A_i. The "*" symbol may represent any operation, such as XOR, multiplication, addition, etc. The data processing instance A_i may record the random mask γ_i, and forward the ciphertext to the key manager P, which may decrypt and record γ_i*K. With respect to the term key manager P as used herein, the functionality described as performed by the key manager P and the information related to the key manager P may be performed by and related to a key manager computing device

For the example system and method disclosed herein, the values K, γ_i, and α_j may be bit-strings of an appropriate length, regarded as elements of a group that is of fixed length bit-strings, with bit-wise XOR as the group operation. The computations $K*\gamma_i$, α_j/K, etc. of the aforementioned key splitting service may be computations in this convenient group. The length of the keys may be selected according to the cryptographic service (e.g., the particulars of the encryption, decryption, or authentication process) for which keys are being managed.

For the example system and method disclosed herein, compared to the use of homomorphic encryption techniques, assuming a key length for a secure symmetric-key system is 256 bits, XOR operations on 256-bit values may be generally more efficient than homomorphic encryption operations. These 256-bit values may be considered secure with respect to cryptanalytic techniques. As computational power increases (e.g., per Moore's law, etc.) and as cryptanalysis improves, these bit lengths may gradually increase. The symmetric-key length may be expected to continue to stay correspondingly shorter than the asymmetric-key lengths. Further, for the example system and method disclosed herein, the need to convert group elements α_j/K into useable symmetric keys is also eliminated, since these values may be used directly as bit-strings. For example, the values K and α_j may be bit-strings of an appropriate length, regarded as elements of a group that is of fixed length bit-strings, with bit-wise XOR as the group operation.

According to an example, the key splitting system may include at least one processor, and a memory storing machine readable instructions that when executed by the at least one processor cause the at least one processor to receive a master key K from an entity (e.g., the data owner U) that is related to data that is to be encrypted, decrypted, or authenticated. A data key S_j that is to be used to encrypt, decrypt, or authenticate the data may be derived from the master key K and a mask γ_i that is received from the entity that is related to the data. The machine readable instructions may further forward a version (e.g., $K*\gamma_i$) of the master key that is masked by using the mask to a key manager P to manage the data key S_j, and generate a data processing instance A_i to utilize the data key to encrypt, decrypt, or authenticate the data. The machine readable instructions may further determine the data key S_j to encrypt, decrypt, or authenticate the data based on a previous data key (e.g., a known S_j) selected by the data processing instance A_i.

FIG. **1** illustrates an architecture of a key splitting system (hereinafter also referred to as "system **100**"), according to an example of the present disclosure. Referring to FIGS. **1** and **2**, the system **100** is depicted as including a data processing instance generation module **102** to generate an instantiation i of a data processing instance **104**, with the i^{th} instantiation of the data processing instance **104** being designated A_i. The data processing instance generation module **102** may implement a data processing instance generation protocol **200** as described herein with reference to FIG. **2**. The data processing instance A_i may be instantiated with the assistance of a data owner **106** (designated U) which holds a master key **108** (designated K) and a virtual key management module **110** (designated P). The data owner U may also select a random mask **122** (designated γ_i) to generate a masked version of the master key K, as described herein with reference to the data processing instance generation protocol **200**. The virtual key management module P, which may be in a system that is separate from a system that includes the data owner U, or which may be in the same system as the data owner U, may facilitate the maintenance of the various encryption keys across different instantiations A_i of the data processing instance **104**. For the data processing instance generation protocol **200**, communication may not be needed between the data owner U and the virtual key management module P.

In order to retrieve decrypted data from a data repository **112** that includes data **114**, the data owner U may initiate a data processing instance A_i. The data processing instance A_i may be ephemeral. The data processing instance A_i may be used to interact with the virtual key management module P in order to reconstruct specific keys. The state between different instantiations of the data processing instance A_i may be maintained by having the data owner U use the same master key K in all instantiations A_i, and by having the virtual key management module P store a masked version of the specific key S_j*K (where S_j represents a string that represents a j^{th} specific key for encrypting, decrypting, or authenticating, or validating the authentication of a data object).

A data repository key generation module **116** of the system **100** may generate a new specific key S_j to be used to encrypt, decrypt, or authenticate, or validate the authentication of the data **114** on the data repository **112**. The data repository key generation module **116** may be implemented by the data owner U and/or by the virtual key management module P, but is shown as being independently implemented in the example of the system **100** of FIG. **1**. The data repository key generation module **116** may implement a data repository key generation protocol **300** as described herein with reference to FIG. **3**. The data repository key generation module **116** may provide for the storage and use of a blinded (i.e., masked) version of this specific key S_j by the virtual key management module P.

A data processing instance key generation module **118** of the system **100** may provide for the data processing instance **104** to dynamically generate specific keys S_j, and to transmit a blinded version of the generated keys to the virtual key management module P. The data processing instance key generation module **118** may be implemented by the data owner U and/or by the virtual key management module P, but is shown as being independently implemented in the example of the system **100** of FIG. **1**. The data processing instance key generation module **118** may implement a data processing instance key generation protocol **400** as described herein with reference to FIG. **4**.

A previous storage object retrieval module **120** of the system **100** may implement the retrieval of a previous storage object from the data repository **112**. The previous storage object retrieval module **120** may be implemented by the data owner U and/or by the virtual key management module P, but is shown as being independently implemented in the example of the system **100** of FIG. **1**. The previous storage object retrieval module **120** may implement a previous storage object retrieval protocol **500** as described herein with reference to FIG. **5**.

For the system **100**, different entities may communicate securely among themselves using channels that are implemented, for example, via Secure Sockets Layer (SSL) or Transport Layer Security (TLS) built on an existing public key infrastructure (PKI). With reference to FIGS. **1-5**, the keys and masking elements K, S_j, α_j, etc. may be bit-strings of the appropriate length (i.e., bit-strings for the cryptographic key processes whose keys are being managed by using the key-splitting protocols of the system **100**), and "+" may be used for exclusive or (XOR).

FIG. **2** illustrates the flowchart of the data processing instance generation protocol **200** for generation of a data processing instance A_i, according to an example of the present disclosure. Although execution of the methods described below is with reference to the system **100** of FIG. **1**, other suitable devices for execution of these methods will be apparent to those of skill in the art. The method described in the flowchart of FIG. **2**, and the methods described in the other figures may be implemented in the form of executable instructions stored on a machine-readable storage medium, such as the memory **806** and/or the secondary data storage **808** of FIG. **8**, by one or more modules described herein, and/or in the form of electronic circuitry.

Referring to FIG. **2**, at block **202**, the data owner U may select the master key K at random (i.e., select a random value for the master key K). Alternatively, the data owner U may retrieve the master key K from a selection of previously generated keys.

At block **204**, the data owner U may select the random mask γ_i (i.e., select a random value for the mask γ_i).

At block **206**, the data owner U may send the master key K XOR the random mask γ_i (i.e., $K+\gamma_i$) to the virtual key management module P. That is, the data owner U may send the random mask γ_i in masked form to the virtual key management module P. The master key K may also be selected by the data owner U who owns the data **114**.

At block **208**, the data owner U may send the random mask γ_i to the data processing instance A_i.

At block **210**, the virtual key management module P may save the master key K XOR the random mask γ_i (i.e., $K+\gamma_i$). That is, the virtual key management module P may save the random mask γ_i masked by K, where $K+\gamma_i$ is determined by a bit-wise XOR operation. With regard to the system **100**, a non-transitory storage medium may be coupled to the virtual key management module P to store any information (e.g., $K+\gamma_i$, α_j, etc.) related to the virtual key management module P.

At block **212**, the data processing instance A_i may save the random mask γ_i. The random mask γ_i may be used by the ephemeral instantiation of the corresponding data processing instance A_i for operations related to data object encryption, decryption, or authentication, or authentication validation. With regard to the system **100**, a non-transitory storage medium may be coupled to the data owner U to store any information (e.g., γ_i, S_j, etc.) related to the data owner U and the data processing instance A_i.

With respect to the data processing instance generation protocol **200**, the secrecy of the master key K with respect to the data processing instance A_i may be ensured by the security of the asymmetric encryption technique that is used. The secrecy of the master key K with respect to the virtual key management module P may be ensured based on the mask being chosen at random, and not being known to the virtual key management module P.

FIG. **3** illustrates the flowchart of the data repository key generation protocol **300**, according to an example of the present disclosure. Based on the set-up of the instance-specific masking $K+\gamma_i$ of the master key K, this instance-specific masking may be used to protect specific keys S_j for encryption, decryption, or authentication, or validating the authentication of storage objects. This may be done by having the data processing instance A_i interact with the virtual key management module P, where the virtual key management module P may store blinded versions of the various specific keys. The data repository key generation protocol **300** may provide for the j^{th} specific key S_j to be accessed by subsequent unrelated instantiations of the data processing instance.

Referring to FIG. **3**, at block **302**, based on blocks **210** and **212** of the data processing instance generation protocol **200** for data processing instance A_i, the virtual key management module P may retrieve or otherwise receive as input the saved master key K XOR the random mask γ_i (i.e., $K+\gamma_i$), and the data processing instance A_i may retrieve or otherwise receive as input the saved random mask γ_i.

At block **304**, the data processing instance A_i may forward a request to the virtual key management module P to generate a new key with index j. As described herein, the new key with index j may be determined based on a random selection by the virtual key management module P.

At block **306**, the virtual key management module P may select α_j at random, and determine $\beta_{ij}=\alpha_j$ XOR (K XOR γ_i) (i.e., $\beta_{ij}=\alpha_j+(K+\gamma_i)$). For block **306**, α_j and β_{ij} may represent masks that are used for blinding purposes.

At block **308**, the virtual key management module P may send β_{ij} to the data processing instance A_i.

At block **310**, the data processing instance A_i may determine the j^{th} specific key S_j as β_{ij} XOR γ_i (which is equal to α_j XOR K).

At block **312**, the data processing instance A_i may save the j^{th} specific key S_j.

At block **314**, the virtual key management module P may save α_j (which is equal to S_j XOR K).

With respect to the data repository key generation protocol **300**, the string S_j output by the data processing instance A_i may represent the j^{th} specific key S_j. In some examples, instead of using the keys S_j directly for handling data, the keys S_j may be fed as inputs to a key-derivation function (KDF) whose outputs are used as data-handling keys. In this manner, related-key attacks may be avoided on the data stored by the virtual key management module P, where the data includes the values $K+S_1$, $K+S_2$, . . . , $K+S_j$, etc.

FIG. **4** illustrates the flowchart of the data processing instance key generation protocol **400**, according to an example of the present disclosure.

Referring to FIG. **4**, at block **402**, based on blocks **210** and **212** of the data processing instance generation protocol **200** for data processing instance A_i, the virtual key management module P may retrieve or otherwise receive as input the saved master key K XOR the random mask γ_i (i.e., $K+\gamma_i$), and the data processing instance A_i may retrieve or otherwise receive as input the saved random mask γ_i.

At block **404**, the data processing instance A_i may forward a request to the virtual key management module P for a new key with index j. As described herein, the new key with index j may be determined based on a random selection by the data processing instance A_i.

At block **406**, the data processing instance A_i may select the j^{th} specific key S_j at random, and determine $\beta_{ij}=S_j$ XOR γ_i, (i.e., $\beta_{ij}=S_j+\gamma_i$).

At block **408**, the data processing instance A_i may forward β_{ij} to the virtual key management module P.

At block **410**, the virtual key management module P may determine α_j as β_{ij} XOR (K XOR γ_i), (i.e., $\alpha_j=\beta_{ij}+(K+\gamma_i)$).

At block **412**, the data processing instance A_i may save the j^{th} specific key S_j.

At block **414**, the virtual key management module P may save α_j (which=S_j XOR K).

With respect to the data processing instance key generation protocol **400**, the string S_j output by the data processing instance A_i may represent the j^{th} specific key S_j. In some examples, instead of using the keys S_j directly for handling data, the keys S_j may be fed as inputs to a KDF whose outputs are used as data-handling keys. In this manner, related-key attacks may be avoided on the data stored by the virtual key management module P, where the data includes the values $K+S_1$, $K+S_2$, . . . , $K+S_j$, etc.

FIG. **5** illustrates a flowchart of the previous storage object retrieval protocol **500**, according to an example of the present disclosure, to retrieve a previous (i.e., an older) storage object from the data repository **112**.

At block **502**, based on blocks **210** and **212** of the data processing instance generation protocol **200** for data processing instance A_i, the virtual key management module P may retrieve or otherwise receive as input the saved master key K XOR the random mask γ_i (i.e., $K+\gamma_i$), and the data processing instance A_i may retrieve or otherwise receive as input the saved random mask γ_i.

At block **504**, the virtual key management module P may retrieve or otherwise receive as input α_j, where α_j is presumably generated with a previous instantiation of the data processing instance designated as A_i'.

At block **506**, the data processing instance A_i may forward a request to the virtual key management module P to request the previously generated key with index j. As described herein, the previously generated key with index j may be determined based on a random selection by the data processing instance A_i.

At block **508**, the virtual key management module P may retrieve α_j, and determine $\beta_{ij}=\alpha_j$ XOR (K XOR γ_i), (i.e., $\beta_{ij}=\alpha_j+(K+\gamma_i)$).

At block **510**, the virtual key management module P may forward β_{ij} to the data processing instance A_i.

At block **512**, the data processing instance A_i may determine the j^{th} specific key S_j as β_{ij} XOR γ_i, (i.e., $S_j=\beta_{ij}+\gamma_i$).

At block **514**, the data processing instance A_i may save the j^{th} specific key S_j. In some examples, instead of using the keys S_j directly for handling data, the keys S_j may be fed as inputs to a KDF whose outputs are used as data-handling keys. In this manner, related-key attacks may be avoided on the data stored by the virtual key management module P, where the data includes the values $K+S_1$, $K+S_2$, . . . , $K+S_j$, etc.

With respect to the data repository key generation protocol **300**, the data processing instance key generation protocol **400**, and the previous storage object retrieval protocol **500**, the specific key S_j may be used to derive a plurality of keys, one for each data object of a set of data objects of the data **114**. Each of the derived keys may be symmetric or asymmetric. The derived keys may be determined so as to form a hierarchy or tree structure, based on the specific key S_j. In the case of a hierarchy of keys for an instance of the trusted platform module (TPM) that is an international standard for a secure cryptoprocessor, each node (in the tree) may include two keys, one symmetric and the other asymmetric.

The modules and other elements of the system **100** may be machine readable instructions stored on a non-transitory computer readable medium. In this regard, the system **100** may include or be a non-transitory computer readable medium. In addition, or alternatively, the modules and other elements of the system **100** may be hardware or a combination of machine readable instructions and hardware.

FIGS. **6** and **7** respectively illustrate flowcharts of methods **600** and **700** for key splitting, corresponding to the example of the key splitting system **100** whose construction is described in detail above. The methods **600** and **700** may be implemented on the key splitting system **100** with reference to FIGS. **1**-**5** by way of example and not limitation. The methods **600** and **700** may be practiced in other systems.

Referring to FIG. **6**, for the method **600**, at block **602**, the method may include generating a master key. For example, referring to FIGS. **1** and **2**, at block **202**, the data owner U may generate the master key K.

At block **604**, the method may include generating a random mask. For example, referring to FIGS. **1** and **2**, at block **204**, the data owner U may generate the random mask γ_i (i.e., generate a random value for the mask γ_i).

At block **606**, the method may include generating a masked version of the master key by using the random mask. For example, referring to FIGS. **1** and **2**, the data owner U may generate the master key K XOR the random mask γ_i (i.e., $K+\gamma_i$).

At block **608**, the method may include forwarding the masked version of the master key to a key manager. For example, referring to FIGS. **1** and **2**, at block **206**, the data owner U may forward the master key K XOR the random mask γ_i (i.e., $K+\gamma_i$) to the virtual key management module P.

At block **610**, responsive to forwarding the masked version of the master key, the method may include receiving a new mask from the key manager. For example, referring to FIGS. **1**-**3**, at block **308**, the data processing instance A_i may receive β_{ij} from the virtual key management module P_i.

At block **612**, the method may include determining a data key based on the new mask and the random mask. For example, referring to FIGS. **1**-**3**, at block **310**, the data processing instance A_i may determine the j^{th} specific key S_j as β_{ij} XOR γ_i (which is equal to α_j XOR K).

According to an example, for the method **600**, generating the masked version may include using an XOR, an addition, or a multiplication operation to generate the masked version of the master key (e.g., see block **206** of FIG. **2**).

According to an example, for the method **600**, determining the data key based on the new mask and the random mask may include determining the data key based on an XOR operation between the new mask and the random mask (e.g., see block **310** of FIG. **3**).

According to an example, for the method **600**, the new mask may be based on a random selection of another mask (e.g., α_j) by the key manager and the masked version of the master key (e.g., see block **306** of FIG. **3**).

According to an example, the method **600** may further include generating a data processing instance to utilize the data key to encrypt, decrypt, or authenticate the data. For example, referring to FIG. **1**, the data processing instance generation module **102** may generate of an instantiation i of the data processing instance **104**, with the i^{th} instantiation of the data processing instance **104** being designated A_i.

According to an example, for the method **600**, generating the data processing instance may further include generating an ephemeral instantiation of the data processing instance to utilize the random mask and the data key to encrypt, decrypt, or authenticate the data, and utilizing another ephemeral instantiation of a data processing instance that utilizes another random mask and another data key to encrypt, decrypt, or authenticate further data.

According to an example, for the method **600**, the data may include a set of data objects, and the method **600** may further include using the data key to derive a plurality of data keys, where each data key of the plurality of data keys corresponds to a respective data object of the set of data objects. For example, referring to FIGS. **1**-**5**, and with respect to the data repository key generation protocol **300**, the data processing instance key generation protocol **400**, and the previous storage object retrieval protocol **500**, the specific key S_j may be used to derive a plurality of keys, where each data key of the plurality of data keys corresponds to a respective data object of the set of data objects.

Referring to FIG. **7**, for the method **700**, at block **702**, the method may include generating a master key at an entity that is related to data. For example, referring to FIGS. **1** and **2**, at block **202**, the data owner U may generate the master key K.

At block **704**, the method may include generating a mask at the entity that is related to the data. For example, referring to FIGS. **1** and **2**, at block **204**, the data owner U may generate the mask γ_i.

At block **706**, the method may include generating a masked version of the master key by using the mask. For example, referring to FIGS. **1** and **2**, the data owner U may generate the master key K XOR the mask γ_i (i.e., $K+\gamma_i$).

At block **708**, the method may include forwarding the masked version of the master key to a key manager. For example, referring to FIGS. **1** and **2**, the data owner U may forward the master key K XOR the random mask γ_i (i.e., $K+\gamma_i$) to the virtual key management module P.

At block **710**, the method may include receiving a new mask from the key manager, where the new mask is related to a previous data key. For example, referring to FIGS. **1**, **2**, and **5**, at block **510**, the data processing instance A_i may receive β_{ij} from the virtual key management module P, where β_{ij} is related to a previous data key S_j.

At block **712**, the method may include determining the previous data key based on the new mask and the mask generated by the entity that is related to the data. For example, referring to FIGS. **1**, **2**, and **5**, at block **512**, the data processing instance A_i may determine the j^{th} specific key S_j as β_{ij} XOR γ_i, (i.e., $S_j=\beta_{ij}+\gamma_i$).

According to an example, for the method **700**, the data may include a set of data objects, and the method **700** may further include using the previous data key to derive a plurality of data keys, where each data key of the plurality of data keys corresponds to a respective data object of the set of data objects. For example, referring to FIGS. **1**-**5**, and with respect to the data repository key generation protocol **300**, the data processing instance key generation protocol **400**, and the previous storage object retrieval protocol **500**, the specific key S_j may be used to derive a plurality of keys, where each data key of the plurality of data keys corresponds to a respective data object of the set of data objects.

According to an example, the method **700** may further include generating a data processing instance to utilize the data key to encrypt, decrypt, or authenticate the data. For example, referring to FIG. **1**, the data processing instance generation module **102** may generate of an instantiation i of the data processing instance **104**, with the i^{th} instantiation of the data processing instance **104** being designated A_i.

According to an example, for the method **700**, generating the mask at the entity that is related to the data may further include generating a random mask at the entity that is related to the data. For example, referring to FIGS. **1** and **2**, at block **204**, the data owner U may generate the random mask γ_i (i.e., generate a random value for the mask γ_i).

According to an example, for the method **700**, the data may include an index. The new mask may be related to the previous data key by the index of the data. For example, referring to FIGS. **1**, **2**, and **5**, at block **506**, the data processing instance A_i may forward a request to the virtual key management module P to request the previously generated key with index j (i.e., the index of the data). The new mask β_{ij} may be related to the previous data key S_j by the index j of the data.

According to another example of a key splitting method, key splitting may include receiving a masked version (e.g., $K+\gamma_i$) of a master key K (e.g., see block **206** of FIG. **2**). The master key K may be masked by using a mask γ_i that is generated at an entity (e.g., the data owner U) that is related to data (e.g., see block **204** of FIG. **2**). Key splitting may further include receiving a new mask β_{ij} that is based on selection of a previous data key S_j and is further based on the mask γ_i that is generated at the entity that is related to the data (e.g., see blocks **406** and **408** of FIG. **4**). A further new mask α_j may be determined based on the new mask β_{ij} that is based on selection of the previous data key S_j and that is based on the masked version of the master key (e.g., see block **410** of FIG. **4**). According to an example, the new mask may be based on a random selection of the previous data key S_j (e.g., see block **406** of FIG. **4**). According to an example, the further new mask may be determined based on an XOR operation between the new mask β_{ij} and the masked version (e.g., $K+\gamma_i$) of the master key (e.g., see block **410** of FIG. **4**).

FIG. **8** shows a computer system **800** that may be used with the examples described herein. The computer system **800** may represent a generic platform that includes components that may be in a server or another computer system. The computer system **800** may be used as a platform for the system **100**. The computer system **800** may execute, by a processor (e.g., a single or multiple processors) or other hardware processing circuit, the methods, functions and other processes described herein. These methods, functions and other processes may be embodied as machine readable instructions stored on a computer readable medium, which may be non-transitory, such as hardware storage devices (e.g., RAM (random access memory), ROM (read only memory), EPROM (erasable, programmable ROM), EEPROM (electrically erasable, programmable ROM), hard drives, and flash memory).

The computer system **800** may include a processor **802** that may implement or execute machine readable instructions performing some or all of the methods, functions and other processes described herein. Commands and data from the processor **802** may be communicated over a communication bus **804**. The computer system may also include a main memory **806**, such as a random access memory (RAM), where the machine readable instructions and data for the processor **802** may reside during runtime, and a secondary data storage **808**, which may be non-volatile and stores machine readable instructions and data. The memory and data storage are examples of computer readable mediums. The memory **806** may include a key splitting module **820** including machine readable instructions residing in the memory **806** during runtime and executed by the processor **802**. The key splitting module **820** may include the modules of the system **100** shown in FIG. **1**.

The computer system **800** may include an I/O device **810**, such as a keyboard, a mouse, a display, etc. The computer system may include a network interface **812** for connecting to a network. Other known electronic components may be added or substituted in the computer system.

The foregoing disclosure describes a number of examples for key splitting. The disclosed examples may include systems, devices, computer-readable storage media, and methods for key splitting. For purposes of explanation, certain examples are described with reference to the components illustrated in FIGS. **1-8**. The functionality of the illustrated components may overlap, however, and may be present in a fewer or greater number of elements and components. Further, all or part of the functionality of illustrated elements may co-exist or be distributed among several geographically dispersed locations. Moreover, the disclosed examples may be implemented in various environments and are not limited to the illustrated examples.

Further, the sequence of operations described in connection with FIGS. **1-8** are examples and are not intended to be limiting. Additional or fewer operations or combinations of operations may be used or may vary without departing from the scope of the disclosed examples. Furthermore, implementations consistent with the disclosed examples need not perform the sequence of operations in any particular order. Thus, the present disclosure merely sets forth possible examples of implementations, and many variations and modifications may be made to the described examples. All such modifications and variations are intended to be included within the scope of this disclosure and protected by the following claims.

What is claimed is:

1. A non-transitory computer-readable medium having stored thereon machine readable instructions that when executed cause a first computing device to:

- perform key splitting without using a homomorphic encryption technique, the key splitting comprising:
  - obtaining a master key;
  - obtaining a random mask;
  - obtaining a masked version of the master key by performing an operation on the master key and the random mask, the operation selected from among an exclusive or (XOR), a multiplication, or a division;
  - forwarding the masked version of the master key from the first computing device to a key manager computing device;
  - responsive to the forwarding of the masked version of the master key, receiving a new mask from the key manager computing device;
  - determining a data key based on an XOR of the new mask and the random mask; and
- use, by a data processing instance in the first computing device, the data key in encrypting, decrypting, or authenticating data.

2. The non-transitory computer readable medium according to claim **1**, wherein the new mask is based on a random selection of another mask by the key manager computing device and the masked version of the master key.

3. The non-transitory computer readable medium according to claim 1, further comprising machine readable instructions that when executed cause the first computing device to:

generate the data processing instance to utilize the data key to encrypt, decrypt, or authenticate the data.

4. The non-transitory computer readable medium according to claim 3, wherein the machine readable instructions to generate the data processing instance comprise instructions to:

generate an ephemeral instantiation of the data processing instance to utilize the random mask and the data key to encrypt, decrypt, or authenticate the data; and

utilize another ephemeral instantiation of a data processing instance that utilizes another random mask and another data key to encrypt, decrypt, or authenticate further data.

5. The non-transitory computer readable medium according to claim 1, wherein the data comprises a set of data objects, and wherein the machine readable instructions further comprise instructions that when executed cause the first computing device to:

use the data key to derive a plurality of data keys, wherein each data key of the plurality of data keys corresponds to a respective data object of the set of data objects.

6. A method comprising:

performing, by a first computing device comprising a hardware processor, key splitting without using a homomorphic encryption technique, the key splitting comprising:

receiving a master key;

receiving a random mask;

generating a masked version of the master key by performing an operation on the master key and the random mask, the operation selected from among an exclusive or (XOR), a multiplication, or a division;

forwarding, by the first computing device, the masked version of the master key to a key manager computing device;

receiving, by the first computing device, a new mask from the key manager computing device responsive to the forwarding of the masked version of the master key to the key manager computing device;

determining, by the first computing device, a data key based on an XOR of the new mask and the random mask; and

using, by the first computing device, the data key in encrypting, decrypting, or authenticating data.

7. The method according to claim 6, wherein the data comprises a set of data objects, and wherein the method further comprises:

using, by the first computing device, the data key to derive a plurality of data keys, wherein each data key of the plurality of data keys corresponds to a respective data object of the set of data objects.

8. The method according to claim 6, further comprising:

generating, by the first computing device, a data processing instance to utilize the data key to encrypt, decrypt, or authenticate the data.

9. The method according to claim 6, wherein the data comprises an index, and wherein the new mask is related to the data key by the index of the data.

10. The non-transitory computer readable medium according to claim 1, wherein the new mask is based on an XOR of a further randomly selected mask, the master key, and the random mask at the key manager computing device.

11. The non-transitory computer readable medium according to claim 10, wherein the further randomly selected mask is randomly selected by the key manager computing device.

12. The method according to claim 6, wherein the new mask is based on an XOR of a further randomly selected mask, the master key, and the random mask.

13. The method according to claim 12, wherein the further randomly selected mask is randomly selected by the key manager computing device.

14. A first computing device comprising:

a processor; and

a non-transitory computer-readable storage medium storing instructions executable on the processor to:

perform key splitting without using a homomorphic encryption technique, the key splitting comprising:

obtaining a master key;

obtaining a random mask;

generating a masked version of the master key by performing an exclusive or (XOR) on the master key and the random mask;

forwarding the masked version of the master key to a key manager computing device;

receiving a new mask from the key manager computing device responsive to the forwarding of the masked version of the master key;

determining a data key based on an XOR of the new mask and the random mask; and

use, by a data processing instance, the data key in encrypting, decrypting, or authenticating data.

15. The first computing device according to claim 14, wherein the new mask is based on an XOR of a further randomly selected mask, the master key, and the random mask.

16. The first computing device according to claim 15, wherein the further randomly selected mask is randomly selected by the key manager computing device.

17. The first computing device according to claim 14, wherein the instructions are executable on the processor to generate the data processing instance.

18. The first computing device according to claim 17, wherein the generated data processing instance is an ephemeral data processing instance.

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